International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249–6890; ISSN(E): 2249–8001
Vol. 10, Issue 2, Apr 2020, 223–236

A NOVEL ARGON BASED MAGNETRON SPUTTERING FOR IMPROVING ENERGY EFFICIENCY IN SOLAR CELLS

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ABSTRACT

Renewable sources of energy are most researched fields in recent times due to rapid decline in availability of fossil fuels. Recent research is aimed to improve the output of solar cells in terms of electrical efficiency. This has been achieved through several methods out of which alteration of physical, electrical and optical properties of solar cells is found to be a novel strategy in recent times with the advent of nano-technology coupled with deposition techniques. A magnetron sputtering process coupled with RF field has been implemented in this research article to deposit Cu, Al and Ag onto the surface of solar cell under controlled process parameters. NO_2 has been used as inert gas among argon to cause ion bombardment of the substrate surface and depositing a thin film with optimal process control parameters fixed at 45W power, 5 – 7 minutes of deposition time. The quality of surface deposition has been analyzed with UV spectroscopy, stylus Profilometer and SEM images. The deposited substrate has been tested in real time and the power efficiency computed at 16.44% compared to non-coated solar cells recorded at 14% indicating the superiority of the proposed work. Magnetron sputtering for coating of solar cells provides a cost effective yet efficient method of improving the efficiency of solar cells for power generation.

***KEYWORDS:** Magnetron Sputtering, Solar Cells, Surface Roughness, Coating Thickness & Efficiency*

Received: Jan 28, 2020; **Accepted**: Feb 18, 2020; **Published**: Feb 28, 2020; **Paper Id**.: IJMPERDAPR202020

Original Article

1. INTRODUCTION

Solar cells have been found to be implemented on a large scale with the increasing demand in need for renewable sources of energy. This is largely attributed to the rapid decline in availability of fossil fuels on a global scale [21]. Solar panel based energy generation provide a compact and efficient method of power generation which could be easily installed and exhibit a minimal maintenance cost in contrast to a significantly high installation cost. Solar panels offer a simple method of energy generation from abundantly available solar irradiation incident on the solar panels which is converted to into equivalent potential. This voltage with appropriate storage systems could be used to provide power during rainy time periods or at times when solar irradiation is not available or very minimal. Research in solar installations and their working principles have been more focused towards optimal power generation which in turn depends on the number of cells used which depends on the scale of application. Cells together forming an array on the other hand have a direct consequence on the cost of the installation. Hence careful and systematic research in design and decision of optimal number of solar cells is quite necessary and challenging in most of the scenarios [16]. An alternate method to the approach of varying the array number to improve efficiency of energy production from cells is to alter the properties of the surface of cells themselves making them to absorb more incident solar radiation through certain coating technologies which are found to increase the rate of irradiation absorbed by the cell when compared to non-coated conventional solar

cells. This has been greatly achieved as observed from the literature with the advent of nano materials which are characteristic of high absorption properties [17]. One such method of coating the given solar cell with nano material through a controlled sputtering process is investigated and experimented in this research article and observations justify a superior performance of the proposed sputtering process with the specified nano material substance. A general sputtering process is illustrated in figure 1.

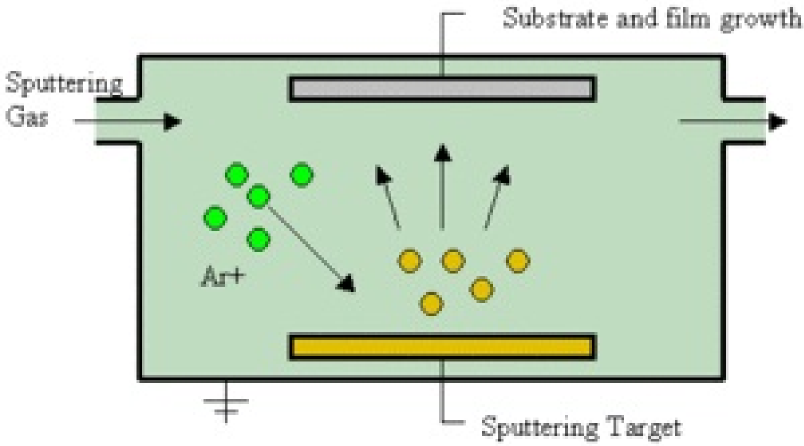

Figure 1: A General Scheme of Sputtering Process.

A general scheme of sputtering involves bombardment of highly ionized gas ions on the surface resulting in vaporization of metal atoms and subsequent deposition on the glass surface. This process results in a fine coating of the desired nano material or any other substance over the target surface in order to manipulate its properties one of which is absorption [18]. This concept is made use of in the proposed work to improve the absorption efficiency of a normal glass cell over the solar cells to ensure maximum absorption of the solar irradiation thereby improving the overall output obtained from the cell [20]. This method helps in improving the efficiency by a significant amount over conventional solar cells given the same size and dimensions at no extra cost excluding the sputtering process. An in depth investigation into the magnetron sputtering process and its application to enhance the properties of the glass substrate using NO_2 has been experimented and analyzed using various methodologies. Utilization of solar cells in domestic and industrial applications is going in an active manner to improve the efficiency and maximum output voltage. Maximum power point tracking is one of the important technique in solar tracking and it has been investigated extensively [5] [19] [24] in the literature. It consists of a motor arrangement with a suitable controller to track the maximum insolation levels throughout the process of the day helps to maintain a stable output for that particular day. Implementing fuzzy controllers in the conventional methods helps to induce intelligence into the tracking methods [22], and also supervised learning based controllers [23] etc helps in improving the ability of tracking and efficiency in power generation. However, the limitation in the MPPT is additional costs in the tracking set up application. Other methods involve research in choice of solar concentrators [4], their design, angle of orientation and sizing optimization of PV cells for a given application. Involving optimization algorithms to investigate the optimal sizing of the solar cells which include genetic based methods, simulated annealing methods; evolutionary algorithms [6] which best simulate the real time scenario are presented in the literature. Limitation of such experimental models leads into cost increasing factor in power generation per unit and also increases the computation while providing optimal sizing. Introduction of nano technology in the solar cell manufacturing increases its absorption property and generates more power than

conventional models. Coating methodologies used in the literature [14] describes about the characteristics of deposition process involved in glass surface as a coating material so that it provides a lossless power generation from the source. Sputtering process are classified into different types depending upon the target application and popular ones include ion beam sputtering [12], Hi-target utilization sputtering [8], reactive sputtering [19] gas flow sputtering [16], high impulse magnetron sputtering [10]. Sputtering process has been used for a wide range of applications popularly in textile industry [1] and deposition of solar cells [7]. Various types of sputtering processes have been actively used for solar cells such as methyl ammonium lead oxide ($CH_3NH_3PbI_3$) with an efficiency of over 19% improvement [6]. This type of sputtering is found to improve the absorption coefficient and characterized with a long diffusion length. Improvements in the above design have been done by introducing hybrid organo – lead trihalide perovskite based solar cells which are characterized by high rates of absorption coefficient [5]. Literature also presents a deposition scheme of Aluminium oxide [7] through reactive magnetron sputtering process on silicon wafers for the purpose of damage control on the surface of the wafer. This experimental setup provides high degree of surface passivation and it has been implemented as low cost solar cells with high operating efficiency. Thin film coatings of molybdenum in copper indium gallium diselenide solar cells [8] are few other variants in the deposition phenomena. Magnetron sputtering has been used in the process and is shown to achieve high adhesion to the surface and simultaneously maintaining the electrical and physical properties of the base material. Multi-layer deposition has been experimented to increase the crystalline nature of the film. Molybdenum based [11] [12] [14] coating has also been experimented along with Cu(In, Ga)Se2 [13] to improve the efficiency of the solar cell by optimizing the back contact of the electrodes with the coating. Research related to improving the back contact of electrodes in solar cells has also been investigated in the literature [10] with polyimide foils for the solar cells. Efficiency improvements of up to 21.7% have been reported in the literature [9] by exploiting the properties of Cu(In, Ga)Se2. From the survey of literature it could be observed that preparation of base material and choice of coating process [15] is quite a critical challenge and defines the efficiency of the sputtering mechanism used to a great extent. This research article is organized into an elaborate proposed experimental setup and procedure in section 2. Section 3 presents the experimental observations tested under varying control conditions to exhaustively analyze and justify the performance of the proposed coating material. Based on the observations, a brief conclusion is provided in section 4.

2. MATERIALS AND METHODS

This research paper has experimented the deposition of copper, aluminum and silver in predefined locations on the target solar cell to improve its efficiency with respect to improving the overall output voltage by increasing the absorption coefficient of the incident solar irradiation. The process has been achieved through magnetron sputtering using DC – RF mechanism and has been procedurally carried out as illustrated in this section.

2.1 Preparation of Substrate

The objective of this research article is to improve the efficiency of the solar cell and hence solar cell becomes the substrate in this work. Solar PV cells of capacity rated at 0.5V with dimensions of 20x40mm as shown in figure 2 have been taken as the substrate or base material.

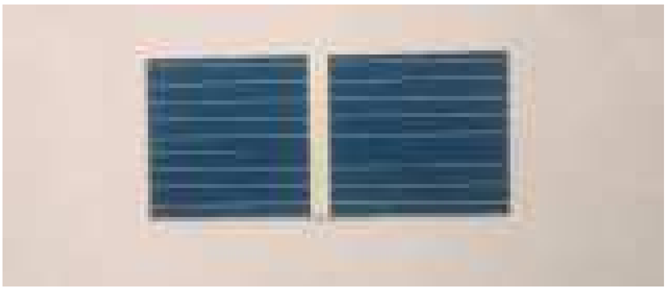

Figure 2: Solar Cell Substrate – 20x40mm.

2.2 Substrate Cleansing

Prior to deposition of thin film over the substrate, the substrate is cleansed through a series of solvents consisting of acetone, distilled water and ethanol. The flow diagram depicting the process as well as the time taken for immersion in each of the solvent solution is shown in figure 3.

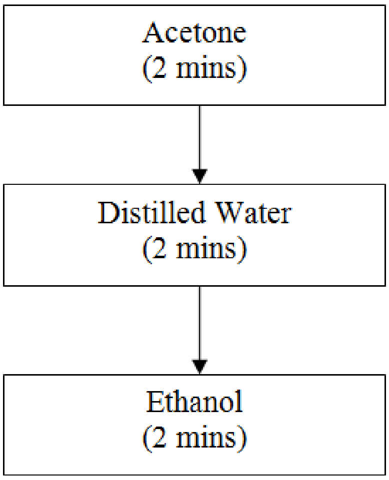

Figure 3: Substrate Cleansing – Flow Process.

Substrate cleansing is an essential process in sputtering process as any dust or any other impurity over the substrate may result in non-uniform coating thus deviating from the efficient performance.

2.3 Experimental Setup

In the proposed sputtering process, magnetron sputtering with RF-DC powered set up is used for providing the controlled coating on the surface of the substrate. The surface is the well treated and cleanses solar cell glass cell over which the deposition is to be made. Choice of magnetron sputtering over other conventional techniques like thermal oxidation, electro deposition is made primarily due to the large area coverage of deposition using the magnetron sputtering process. Further, this large area of deposition is achieved with high rate of deposition concentrate which is also uniform throughout the target area. Moreover, compared to conventional electro chemical methods involving electrodes and acidic solvents which pose a threat to environment and require careful handling, magnetron sputtering is nonpolluting and is easy to handle procedurally. Since the target substrate under study in this research work is a solar cell aimed to collect maximum solar irradiation, the optical properties are quite critical and hence need to be controlled at will to maintain the overall stability of the system. Compared to other techniques, sputtering has a better control over the optical properties of the substrate material. Further, magnetron sputtering is characterized by a high absorption coefficient, higher degree of

adhesion thus increasing its lifetime. Further it employs a simple experimental set up, cheap and provides flexibility in controlling the rate of deposition in a more convenient manner. A simple RF powered magnetron sputtering set up is depicted in figure 4.

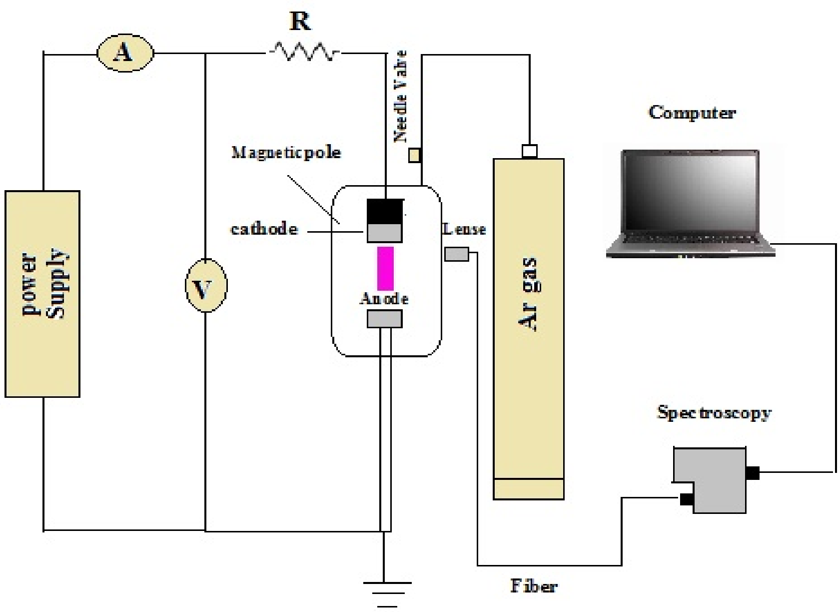

Figure 4: Magnetron Sputtering – Experimental Set up.

As depicted in figure 4, the PC controlled RF powered magnetron sputtering set up consists of anode and cathode. On application of a high RF potential rated at 13.56MHz, magnetic flux lines parallel to the target material are generated in which the electrons get trapped in the space above the target substance which enhances the rate of ion bombardment. The flux lines generated from them magnetic dipoles are quite strong enough to trap the electrons with Argon being popularly being used as the inert gas for the bombarding process. Thin film deposition using the above method is achieved by the reaction between the inert gas and the material to be deposited on the surface of the substrate.

3. RESULTS AND DISCUSSIONS

The experimentation has been carried out in a systematic manner under laboratory conditions of temperature and pressure using a standard magnetron sputtering equipment as depicted in figure 5.

Figure 5: (a). Sputtering Equipment (b). Controls for the Experimentation (c). Sputtering Chamber.

The base material is solar cell as mentioned in previous sections and the target film to be deposited consists of slices of copper, aluminum and silver as shown in figure 6.

Figure 6: Deposition Materials used for Sputtering (Cu, Al, Ag).

Deposition over the cleansed substrate is done under controlled conditions and extensive analysis has been done using a stylus Profilometer for studying the coating properties, SEM images to determine the surface morphology and UV spectroscopy to study the absorption rate.

The first part of the process involves deposition using the process parameters under three different conditions for all the three base materials Cu, Al and Ag. The process parameters used in the sputtering process is listed in table 1. The process control parameters used in the proposed work are power measured in watts, the deposition time measured in minutes and deposition temperature measured in degree.

By appropriate control of flow of Ar gas inside the sputtering chamber and maintain the process control parameters at optimal levels as depicted in table 1, a uniform deposition is carried out at a pressure of 3×10^{-6} bar to ensure a coating of Cu (99.9%), Al (99.9%) and Ag (99.9%). The required levels of deposition have been successfully achieved by varying the process control parameters in a proportional manner. The second part of the work deals with analyzing the deposition process in terms of the coating, roughness and absorption which forms the primary objective of this research work. The observed values of coating thickness and roughness measured using stylus Profilometer are listed in table 1.

Table 1: Performance of Proposed Work under varying Process Control Parameters

Trial No	Power (W)	Deposition Time (min)	Deposition Temperature (^oC)	Coating Thickness (nm)	Surface Roughness R_a (nm)
1	15	3	100	49.640	1.33
2	15	5	200	70.466	2.37
3	15	7	300	61.359	3.19
4	30	3	100	150.620	2.55
5	30	5	200	138.286	2.99
6	30	7	300	160.079	5.01
7	45	3	100	310.670	5.03
8	45	5	200	227.415	5.90
9	45	7	300	203.500	6.76

From table 1, it could be observed that increasing the power increases the coating thickness and subsequently the surface roughness in nanometers. It could be observed that a more or less linear relationship exists between the increase in input power and coating thickness but at the same time it could be observed that the roughness does not increase as much as the thickness. In spite of increase in thickness of coating which increases in the rate of magnitudes of nearly double, it could be seen that the change in surface roughness in hardly by 2% with increasing levels of power intensity. Temperature and time can have a significant effect on the coating thickness. Exposing the substrate for longer time towards

bombardment from argon ions, the thickness increases and a slight increase in roughness is also observed. From the above study, an average roughness of 6nm is obtained at optimum power levels of 45W with a deposition rate of 5-7 minutes. The visual plots of coating thickness and surface roughness obtained from Profilometer is depicted in figure 7.

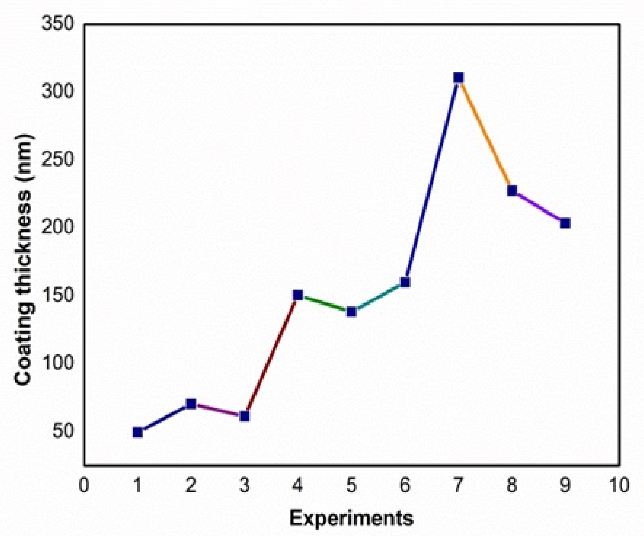

Figure 7: Effect of Coating Thickness vs Trial Number.

It could be observed from figure 7 that a stable and optimal level of coating thickness is obtained at trial no 9 which corresponds to a power level of 45W with a deposition time of 7 minutes and temperature of 300degrees. A similar plot for visualizing the surface roughness is depicted in figure 8 shown below.

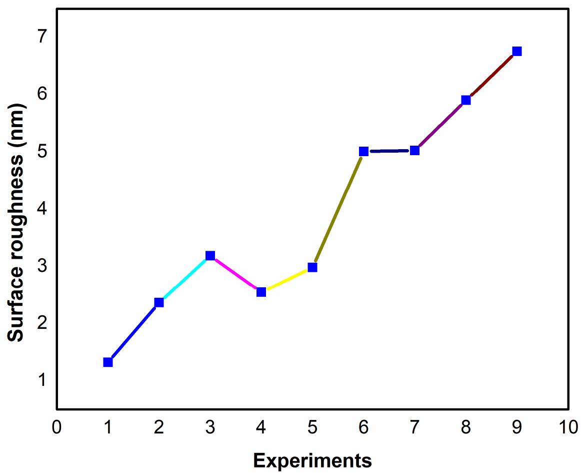

Figure 8: Effect of Surface Roughness vs Trial Number.

From figure 8, it could once again observed that an optimal and stable level of roughness could be observed at a power level of 45W with a deposition rate varying from 5 – 7minutes with a temperature variation from 100 – 300 degrees. The next part of the analysis lies in studying the surface morphology of the deposited surface scanning electron microscopy (SEM) images. SEM images are highly useful in analyzing the internal structure of the materials, the interaction and uniformity of deposition on the base metal. They give a precise analysis of the concentration of each base material or coating material present inside the target substance or substrate. Out of the samples taken, the images corresponding to the depicted trial numbers are presented in figure 9.

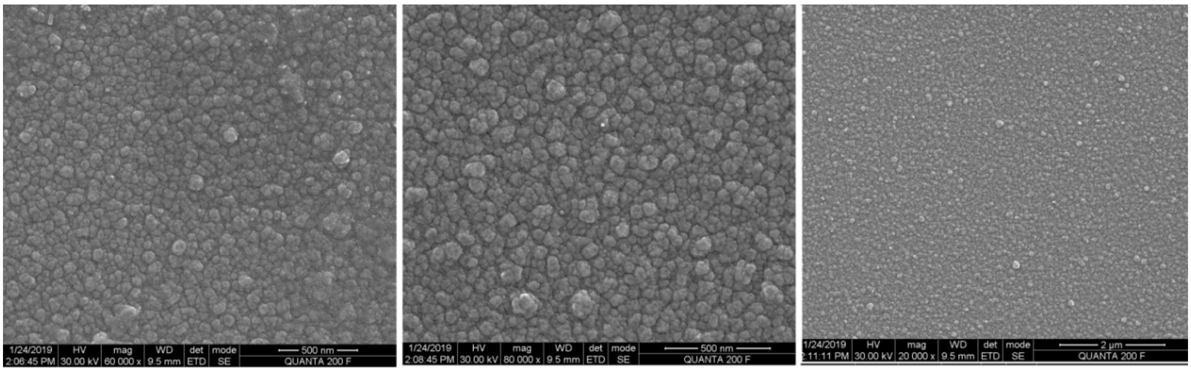

Figure 9: Surface Morphological Analysis.

Three different conditions of deposition are illustrated in figure 9 where it could be seen that the initial sample corresponds to deposition of Cu, Al and Ag at a power level of 15W and 100 degree and characterized by irregular molecular structures where increasing the power level to 30W causes a more or less closely packet molecules with the final image depicting a densely packed fine shaped materials inside the substrate corresponding to a power level of 45W with a deposition time ranging from 5 – 7 minutes. The reduction in grain size of deposited material varies from 50nm to 80nm and hence accounting for the closely packet structure thus ensuring maximum adhesion.

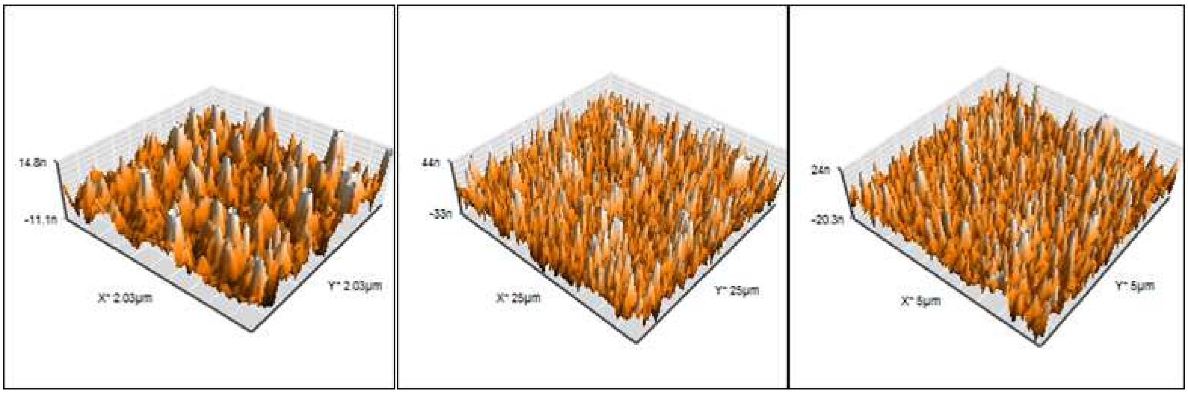

Figure 10: Surface Topographical Analysis.

The AFM images for surface topography analysis on coated area is shown in Figure 10 under different operating condition from 15W to 45W which indicates that the surface has many spikes which confirms the surface is not smooth and also shows the variation in the surface with less inter grain space due to increase the sputtering power. This rougher surface can create more reflection and bounce back into the surface thereby increase the output power of the PV cell.

The next part of the analysis includes the utilization of ultra violet spectroscopy to compute the absorption ratio of the coated surface. It is a well-known fact that high energy light characterized by a shorter wavelength and hence a high absorption ratio which is characteristic of solar irradiation relative to those with higher wavelength which have low absorption ratios. Absorption is basically attributed to the interaction between a photon and electron to enable them to excite to a higher level. Substances in which energy of photons are equal to the band gap energy are characterized by lower absorption ratio. Electrons in the valence band primarily contribute to the absorption of the photon by the surface due to aggregation of valence electrons on the substrate. Based on the above concept of interaction and extinction, the absorption ratio could be computed as

$$AC = \frac{4\pi E}{\lambda} \tag{1}$$

Where E depicts the extinction coefficient and AC, the absorption coefficient. In the proposed work the absorption coefficient of the thin film coated substrate through the magnetron sputtering process is analyzed using UV spectroscopy.

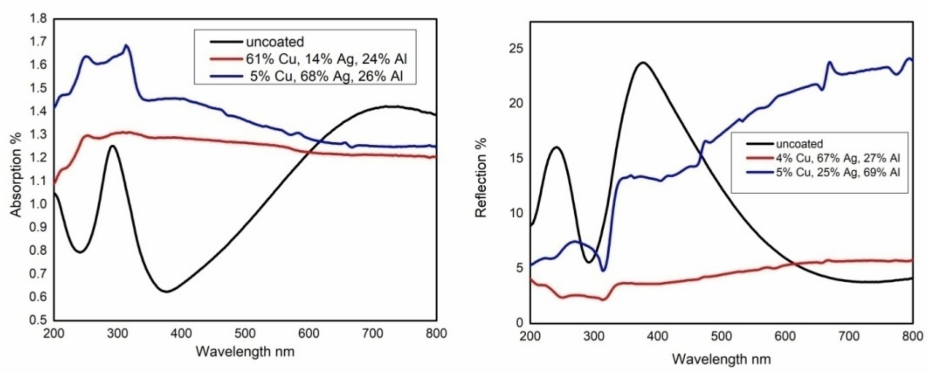

Figure 11: Absorption and Reflection Coefficient Analysis.

Figure 10 depicts the analysis of absorption ratio and reflection ratio of uncoated and coated substrates with varying levels of deposition as depicted in the figure. It could be seen that uncoated substrates exhibit the least absorption coefficient indicated by the black plot and exhibiting maximum reflection relative to the coated substrate which exhibit maximum retainment of incident energy as indicated by the red and blue lines. The red plot corresponds to a deposition rate of 61% Cu, 14% Ag and 24% Al which is further improved with a concentration of 5% Cu, 68% Ag and 26% Al. A high reflection percentage of up to 23% is reported in the uncoated sample which is drastically reduced down to 3.67% after coating with Cu, Ag and Al and varying the concentrations of the individual deposition elements.

The final analysis involves testing the thin film coated solar cell for its power efficiency under laboratory conditions and various electrical metrics and measured for two different samples. The results measured have been tabulated in table 2 shown below. The current – voltage characteristics of the coated and uncoated cell is depicted in figure 11.

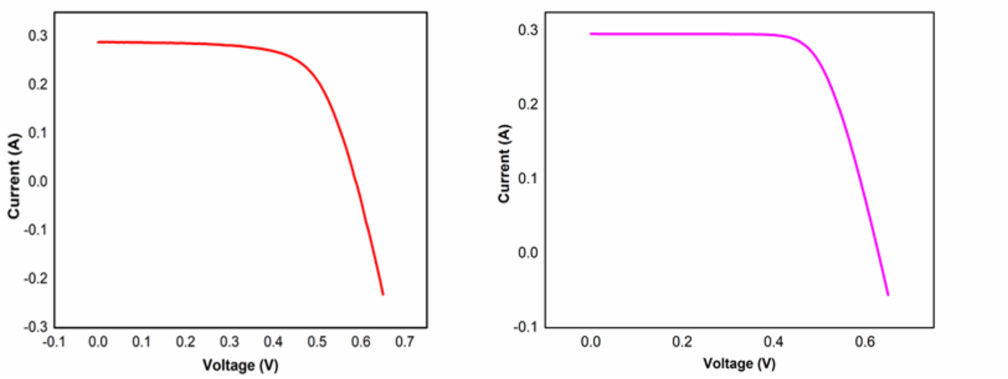

Figure 12: I-V Characteristics of uncoated and Coated Solar Cell.

Table 2: Electrical Properties of uncoated and Coated Solar Cell

Sample No	Open Circuit Voltage V_{oc} (v)	Short Circuit Current I_{sc} (A)	Max Voltage V_{max} (V)	Jmp Current Density at P_{max} (A/cm^2)	Short Circuit Current Density J_{sc} (A/cm^2)	Max Power P_{max} (mW)	Fill Factor (%)	Efficiency (%)
1(Reference)	0.5877	0.2887	0.4534	0.0313	0.0360	113.88	67.04	14.22
2 (coated)	0.6290	0.2959	0.4745	0.0346	0.0369	131.59	70.69	16.44

From table 2, it could be seen clearly that two different samples have been tested and its electrical properties have been measured. Sample 1 refers to uncoated solar cell while sample 2 refers to coated solar cell. The coating has been done with optimized process control variables as illustrated previously. It could be seen that the coated cell produces an electrical efficiency of nearly 16% in comparison to the non-coated solar cell reporting only 14% efficiency thus justifying the efficiency of the proposed work.

4. CONCLUSIONS

Solar cells are being researched in great numbers in recent times due to increasing demand for renewable sources of energy. With the advent of nano technology and state of the art coating and deposition techniques in mechanical engineering, modification of solar cells to enable them to absorb more energy compared to conventional cells have been investigated in the recent past. A great deal of research has been carried out using several deposition methods and materials ranging from copper, molybdenum, silver, aluminum etc. These materials tend to alter the optical and electrical properties of the substrate over which they are deposited. This has been made use of in this proposed work where a magnetron sputtering process powered by a RF field has been implemented to coat the base solar cell with Cu, Ag and Al under controlled process control parameters. The experimentation and analysis has been done in four stages namely deposition and utilizing optimized process control methods to arrive at optimal concentrations, analyzing the coating properties and surface morphology using SEM images, estimation of absorption ratio of the coated surface using UV spectroscopy and computation of power efficiency in real time. Optimized values of 45W of power, 5-7 minutes of deposition time followed by a temperature maintained from 100 – 300 degrees has been found to be the ideal process control parameters to provide the desired coating. It could be found the experimental results that a non-coated solar cell exhibits 23% reflection indicating a non-optimal performance when compared to 3.67% reflection ratio for a coated surface. A high degree of absorption is witnessed in the coated cell which is further substantiated by the overall power efficiency improvement of up to 16% in real time. Further investigations into optical modulating nano coating materials could be considered and investigated as a future scope of research.

ACKNOWLEDGEMENT

The authors would like to thank Centre for Nanoscience and Nanotechnology, Sathyabama institute of science and Technology for providing Magnetron sputtering Coating facility and Stylus Profilometer instrument for measuring Surface roughness and coating thickness. We extend our thanks to IIT Madras for SEM facility and CIF in Pondicherry University for measuring optical properties.

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